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DEVELOPMENT AND EVALUATION  
OF A PLASMA GENERATOR WITH A FILM COOLED ANODE

A THESIS

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## DEVELOPMENT AND EVALUATION

# OF A PLASMA GENERATOR WITH A FILM COOLED ANODE

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## TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS . . . . .	ii
LIST OF TABLES . . . . .	iv
LIST OF ILLUSTRATIONS . . . . .	v
SUMMARY . . . . .	vi
Chapter	
I. INTRODUCTION . . . . .	1
II. DISCUSSION OF THE PROBLEM . . . . .	9
III. EQUIPMENT AND INSTRUMENTATION . . . . .	14
Plasma Torch	
Calorimeter	
Power Source	
Cooling Water	
Gas Supply	
Instrumentation	
IV. TESTING PROCEDURE AND RESULTS . . . . .	20
V. DISCUSSION OF RESULTS . . . . .	23
VI. CONCLUSIONS AND RECOMMENDATIONS . . . . .	27
APPENDIX . . . . .	28
BIBLIOGRAPHY . . . . .	44

## LIST OF TABLES

Table		Page
1.	Water Cooled Torch Test Results . . . . .	28
2.	Film Cooled Torch Test Results . . . . .	29

## LIST OF ILLUSTRATIONS

Figure		Page
1.	Plasma Torch Schematic . . . . .	30
2.	Arc Energy Transfer Processes . . . . .	31
3.	Film Cooling . . . . .	32
4a.	Plasma Torch with Film Cooled Anode . . . . .	33
4b.	Water Cooled Anode . . . . .	34
5.	Experimental Apparatus Schematic . . . . .	35
6.	Calorimeter . . . . .	36
7.	Torch Efficiency versus Arc Current . . . . .	37
8.	Torch Efficiency versus Gas Flow Rate . . . . .	38
9.	Energy Flow Diagram . . . . .	39

## SUMMARY

As a result of the recent surge of interest in such fields as melting, spraying and cutting refractory materials; high temperature research; laboratory simulation of re-entry; low thrust space propulsion and other thermally severe environments, the requirements for high temperature gases such as produced by plasma torches have increased considerably. Because of the increased demand for plasmas, attention has been focused on the efficiency with which electrical energy is converted to thermal energy in a torch. Efficiency, in this instance, is defined as the ratio of the energy content of the emerging gas stream to the electrical energy input.

Recently, regenerative cooling methods have been successfully used to cool plasma torches and have produced higher operating efficiency. Torches with transpiration cooled anodes have produced efficiencies of 80 to 90 per cent, compared to 50 to 70 per cent efficiencies for the conventional water cooled torch.

The purpose of this work is to investigate still another regenerative cooling method - film cooling. A gas stabilized constricted arc type torch was constructed with interchangeable water cooled copper and film cooled carbon anodes for use with argon. Also, a shell and tube calorimeter was constructed to determine the energy content of the torch effluent.

Tests were conducted with each torch in which arc current and gas flow rate were selected as the operating variables. Also, two test runs were made using the film cooled torch, during which the arc current and primary gas flow rate were maintained constant, while the secondary



(coolant) flow was varied. The test results indicate that for approximately the same total gas flow rate and arc current, the torch equipped with a film cooled carbon anode is approximately 20 per cent more efficient than a fully water cooled torch. The film cooled torch efficiency ranged from 80 to 90 per cent, while the water cooled torch efficiency ranged from 60 to 70 per cent for gas flow rates between 0.20 lbs/min to 0.57 lbs/min. An error analysis indicates that these efficiencies are correct within  $\pm$  seven per cent.

## CHAPTER I

### INTRODUCTION

Gases hot enough to be partially ionized have been used and studied for over 100 years. Such a gas is generally referred to as a plasma. It should be noted, however, that according to Langmuir's original definition, the word "plasma" strictly denotes an electrically neutral gas containing high concentrations of electrons and heavy ions.

Plasmas have many applications. Some of the more common ones include fluorescent lighting tubes, neon lights, welding arcs, and mercury and carbon arc lamps. Originally, however, plasmas were applied in the fields of chemical and refractory processing.

At the beginning of this century, a process was developed by Birkeland and Eyde (1)\* for the synthesis of nitric oxide from air, utilizing a plasma flow. Similar developments include a nitrogen-fixation process and the synthesizing of acetylene from saturated hydrocarbons. Now, compounds such as titanium nitride, magnesium nitride, cyanogen, and nitrogen dioxide are being synthesized from the elements with the application of plasmas.

In the field of refractory processing, plasmas were originally used for heating high temperature furnaces. Subsequent innovations in the methods of plasma production have greatly simplified the processes of melting, spraying, and cutting of refractory materials.

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\*Numbers in parentheses refer to references in the literature cited section.

Fabrication of new types of laminated materials is now possible through the application of plasma spraying techniques. This new development provides a means of spray-plating a metal with such refractories as zirconium oxide with a bonding strength heretofore not believed possible. Other spray materials include aluminum oxide, chromium boride, hafnium carbide, porcelain powder, silicon, tungsten carbide, titanium carbide, tantalum, stainless steel, and others.

Complementary to the plasma spraying process in which material is added to a surface, is the cutting process in which material is removed from the work piece. As a result of the recent advances in plasma generation, the plasma cutting process is no longer restricted to refractory materials. It has been found economically feasible to cut thick sections of steel, aluminum, and other metals with plasmas. By applying the techniques used for cutting, materials may also be shaped. The surfaces to be removed are sprayed by the plasma and the melt is vaporized and blown away. In addition to the spraying, cutting, and shaping processes, it is also possible to weld even the most difficult refractories with a plasma.

Plasmas have been frequently applied in the space exploration program. At the beginning of the ballistic missile program in 1954, the need arose for an energy source capable of evaluating ablative materials under simulated re-entry conditions. A plasma flow was used and has since proven to be an important research tool for material evaluation. Now, however, with the development of recoverable satellites, boost-glide vehicles, and lunar probes, the requirements for sustained simulation of high enthalpy flight are more severe, requiring in some instances heat

fluxes as high as 20,000 Btu/ft<sup>2</sup>-sec. Only plasma flows can meet such thermally severe requirements.

Magnetohydrodynamic applications of plasma flows include MHD energy converters, MHD power generators, MHD plasma propulsion engines, ion engines, and MHD plasma foils. The application of plasma flows in power converters has attracted attention because the conventional heat engine is eliminated, thereby improving the converter efficiency.

During the past decade, the accelerated space exploration program has also greatly increased the demand for plasmas. This increase in demand is largely responsible for the rapid development of plasma production technology. These plasmas can be produced in a number of different ways: chemical reactions of high specific energy; "seeding" a pre-heated gas flow; radio-frequency heating; and electric arc heating.

Chemical reactions, including the combustion of fossil fuels and nuclear reactions, produce plasmas whenever sufficient energy is released to ionize a major portion of the gas stream. Examples of this type of plasma generation include rocket engine exhaust and fusion reactor effluents.

Experimental work is now being conducted on a plasma generation process in which a heated gas flow is "seeded" by a secondary gas flow (2). The term "seeding" refers to the injection of a gas with a low ionization potential. The primary gas flow must be pre-heated so that the energy level is high enough to ionize the secondary gas flow.

Another relatively new method of plasma production involves the application of radio-frequency heating to a supersonic gas stream. This method of heating has particular merit because it does away with electrodes

and thus eliminates one of the major problems in the electrical production of plasmas. In hyperthermal wind tunnels, addition of the heat downstream has the added advantage of alleviating the throat cooling problem and reducing the energy loss from the gas stream. The one disadvantage to using radio-frequency heating as a means of plasma production is the high cost of RF power equipment.

The most frequently used method of plasma production involves the passage of a gas through an electric discharge. This can be accomplished by establishing two conducting electrodes in contact with a gas flow and connecting these electrodes to a supply of electrical energy such as a battery or generator. Once a current path is established, for instance by a high voltage discharge, a current will flow with only a relatively low voltage across the electrodes.

The production of plasmas utilizing electric arcs has many advantages over most of the other production methods. For instance, plasmas produced by chemical combustion have an upper temperature bound of approximately 10,000° F and are, by necessity, heavily contaminated by the products of combustion. On the other hand, the upper temperature limits for the electrically produced plasmas have not been determined, but are known to be considerably higher than 10,000° F, and the contamination level of the heated gas stream is less than one per cent when either thoriated tungsten or cooled copper electrodes are used.

Arc plasma generators are capable of converting large quantities of electrical energy to thermal energy. Generators with an electrical input in the megawatt range are presently being used. Also, arc plasma generators can be operated with a number of different gases. Considerable

experimental work has been expended on the operation of generators with such gases as air, ammonia, argon, helium, hydrogen, and nitrogen. Other gases may be used provided that sufficient energy is added to the gas stream to cause decomposition and ionization.

Arc plasma generation also has some problems. In order to prevent severe material loss or failure, special cooling methods must be employed in the areas subjected to high heat fluxes. Also, as the temperature of the plasma increases, the energy losses, particularly radiation, increase substantially, thereby reducing the energy conversion efficiency. Of particular importance when arc plasma generators are used in re-entry simulation, is the decreasing efficiency with increasing chamber pressure. This effect may prove to be a fundamental limitation upon the production of high pressure, high temperature gases using plasma generators. In spite of these disadvantages, arc plasma production remains the most practical and desirable production method for generating thermal plasmas.

Arcs were employed in the production of plasmas as early as 1910, when a generator with consumable carbon electrodes was used to heat high temperature furnaces (3). Shortly thereafter, in 1922, two German scientists, Geriden and Lotz, developed a water stabilized arc which was used primarily as a high temperature research tool (4). Subsequent developments occurred primarily in the fields of chemical synthesis and refractory processing.

A major fraction of the arc plasma generation technology presently available has been developed in the past decade primarily as a result of the influence of the space exploration program. Experimental work has

been conducted, utilizing generators of many different sizes and configurations. Despite these differences, most models are characterized by:

(1) Rotational symmetry about a central axis.

(2) Coaxial electrodes separated by an annular gap across which the arc current passes and through which the gas flows.

Due to the energy loss from the arc, the confining walls and electrodes of the generator must be cooled to prevent excessive material loss or failure. Until recently, most models, including those commercially available, have been constructed with water cooling passages around the electrodes and constrictor walls. A pumping system is used to supply the required quantity of water. This is a very effective cooling method, and if the proper quantity of coolant is supplied, the material loss is negligible. However, the energy loss to the cooled metal surfaces, especially in the anode region, is considerable. Consequently, the generator efficiency defined as the ratio of the thermal energy output to the electrical energy input, is low. Reported efficiencies of water cooled generators range from 40 to 70 per cent, depending on the power level, chamber pressure, gas flow rate, and generator size (5, 6).

Because of the low efficiency and the immobility of the water cooled generator, other cooling methods are being investigated. Particular emphasis has been placed on the mass transfer and regenerative cooling methods such as ablation and transpiration.

Ablative electrodes were used in some of the original generators. This type of electrode is constructed of an electrically conducting material with refractory properties such as carbon. As the surface is heated, the material decomposes or sublimates, absorbing the latent heat

associated with the change of phase. This method of cooling does produce improved efficiency; however, the operating time is limited by the ablation rate of the electrodes. Also, the torch effluent is contaminated with the electrode material and is not suitable for material evaluation and chemical process work.

The application of transpiration cooling in plasma torch construction has been more successful. This method incorporates a porous refractory anode which is cooled by a transpiring gas stream flowing through the material. Torches with transpiration cooled anodes have produced efficiencies between 80 and 90 per cent (7). Material loss during a four hour test was less than one per cent of the original weight and a decreasing rate of ablation was reported. Thus, the transpiration cooled torch is capable of efficient, stable operation for indefinitely long periods of time.

Applications of the transpiration cooled anode appear to be limited, however, due to the structural weakness of the porous anode. Since a greater porosity is required for added coolant flow with increasing power input, the operating power level is thereby limited. In order to retain the improved efficiency afforded by mass transfer cooling, but to reduce the structural and contamination problems associated with transpiration and ablation, a torch equipped with a film cooled anode was designed and constructed as a part of this investigation.

Similar to transpiration cooling, film cooling takes advantage of the regenerative effect of the coolant flow. However, rather than pass the coolant through the material to be protected, film cooling, as the name implies, utilizes an insulating film of coolant injected through a slot or annulus parallel to the surface to be cooled.



Since film cooling does not require a porous material, solid refractory materials which are good electrical conductors, such as tungsten, solid carbon, and metalized or carbonized ceramics, may be used. Consequently, the power input is limited by the cooling effect of the film rather than the strength of the material.

A considerable amount of experimentation has been conducted with plasma generators cooled by ablation and transpiration. Both free-burning and constricted arc applications have been studied (7, 8). As far as could be determined, however, film cooling as applied to plasma torches has not been investigated.

Like transpiration cooling, film cooling has been used to protect nozzle walls in turbo-jets and rocket engines from the extremely high temperature exhaust gases. The basic film cooling theory is provided by Eckert (9). The influence of various coolant slot configurations has been reported by Eckert and Birkebak (10) and the effectiveness of the cooling film has been studied by Hartnett, et al. (11).

The principal objectives of this investigation were to design, construct, and evaluate a torch equipped with a film cooled anode. In order to compare directly the results obtained from both film cooled and water cooled anodes, the torch was constructed with interchangeable water cooled copper and film cooled carbon anodes. The water cooled anode is taken as the standard for comparison because of its wide use. The results from the film cooled test are also compared with previously reported transpiration cooled results (7).

## CHAPTER II

### DISCUSSION OF THE PROBLEM

As shown in Figure 1, the plasma torch used in this work is of the gas stabilized constricted arc design, consisting of three principal components: a combination cathode and gas injection section, a constrictor section, and an anode section.

The gas flow regime indicated in Figure 1 was postulated and experimentally verified by John, et al. (5). The regime consists of three regions: core flow, inner flow, and outer flow. The arc current passes through the central core region, which is aerodynamically positioned along the central axis.

From a macroscopic analysis, the electrical energy is radially transferred to the gas in the inner flow region as a result of the ohmic heating in the core flow region. The thickness of the inner and core flow regions increases with an increase in distance from the cathode, and the inner flow region completely fills the constrictor tube at the point of arc termination. The outer flow region is assumed, for purposes of analysis, to be unaffected by the energy transfer processes.

In order to develop a more efficient torch, it is first necessary to closely examine the energy losses from the arc. In the cathode section, losses are usually very small. Several investigations (5, 12) have indicated that these losses are less than five per cent of the total power input. Energy is lost in the cathode section as heat is conducted away

from the hot cathode surface through the solid metal. Also, energy is transferred by radiation from the cathode and the hot plasma to the surrounding surfaces.

Energy losses in the constrictor section are greater than those in the cathode section. The investigations noted above indicate that the losses in the constrictor may be as much as 15 per cent of the power input, depending on the constrictor geometry and operating parameters such as gas flow rate, power input, chamber pressure, etc. These losses result primarily from the radiation from the arc column to the retaining walls.

The anode section is the area, however, in which the energy losses are greatest. Losses in this section may range as high as 35 per cent, depending also on the geometry and the operating parameters mentioned above.

Losses in the anode section involve a number of different energy transfer processes. First of all, since the inner flow region has completely filled the torch channel, losses by convection are significant. Energy is also lost as a result of the radiation from the arc column to the anode surface. Additionally, energy proportional to the electronic work function is transferred to the anode surface when the electrons are absorbed by the anode material in the arc attachment region. Also, kinetic energy acquired by the electrons in passing through the anode fall zone is transferred to the anode. Figure 2 illustrates the various arc energy transfer processes.

The above analysis of the energy losses assumes that the torch is cooled by a non-regenerative process in which energy transferred to the surfaces is wasted by the cooling process. A water cooled torch is an

example of such a system.

It is obvious from this analysis that any attempt to improve the torch energy conversion efficiency should begin with the anode section. Since the heat fluxes in the anode section are much greater than in the constrictor or cathode, cooling methods that will protect the anode surface will also protect the constrictor and cathode surfaces.

Cooling methods for surfaces exposed to plasmas, especially in the anode region must satisfy many requirements. Primary consideration must be given to arc termination or attachment phenomena. Since the electrons give up energy proportional to the work function of the anode material at the point of attachment, arc attachment over a relatively large area is desirable to prevent anode melting. However, in a water cooled anode where the gas is considerably hotter than the metal walls and where the ionization energy of the gas is greater than twice the work function of the metal (6) the arc will contract and attachment at a point will occur with resultant high local heat fluxes. Consequently, the point of attachment must be rotated either by irregularities in the gas flow, by tangential injection of the primary gas or by an imposed magnetic field to prevent anode burnout.

Obviously, it would be desirable to develop a cooling method which would protect the anode surface, but would also allow operation at a sufficiently high temperature so that the arc attachment would be diffuse. Several investigations (7, 8) have shown that in carbon anode regions cooled by transpiration and ablation the arc attachment is diffuse and, where efficiency studies have been made, improved efficiency has been noted. As noted in Chapter 1, since both of these methods have certain

disadvantages, still another regenerative cooling method - film cooling - has been applied in this investigation.

A film cooling process as applied in this work involves the introduction of a coolant through a slot tangential to the surface to be protected as shown in Figure 3. In a plasma torch this injection effectively extends the inner flow region and provides an insulation layer to protect the walls from the hot plasma. The protection provided by the film is determined by how rapidly the injected mass and momentum of the coolant gas is transported toward the free stream. The parameter of particular interest in this application, however, is the "effectiveness" of the film defined as a dimensionless ratio of the adiabatic wall temperature of the protected surface minus the free stream temperature to the temperature of the entering coolant minus the temperature of the free stream (11). The "effectiveness" is a function of the following parameters:

- (1) Reynolds number of the injected coolant.
- (2) A dimensionless distance from the coolant slot.
- (3) Slot geometry.
- (4) Free stream Reynolds number.

Hartnett, et al. (11) developed and experimentally verified a correlation between the effectiveness and the above parameters for low temperatures and low velocities.

Film cooling utilizes a solid anode material such as tungsten, solid carbon, or metalized or carbonized ceramics all of which have greater strength than porous material required for transpiration cooling. Also, if the proper coolant flow is provided, the loss of anode material is negligible and as a result, a constant geometry torch is maintained. This is

an advantage over torches cooled by ablation since considerable material is lost in the ablative cooling process.

Still another design consideration which is satisfied by the film cooling solution is simplicity. Water cooled torches must be designed with removable anodes so that the anode section can be replaced whenever burnout occurs. As a result, gaskets and o-rings must be used as water seals. With a film cooled torch, it is only necessary to replace the anode insert.

The design parameters to be optimized in film cooling with a given gas as indicated by the previously cited references are the length of the anode, the secondary mass flow rate and temperature, and the velocity of the secondary gas flow. The optimum solution should, for a particular primary gas flow rate, chamber pressure, and power input, provide sufficient secondary mass flow at the proper velocity to protect the anode surface so that a minimum of the anode material is lost by erosion or melting. However, the anode should not be cooled so well that the arc would contract, causing local attachment. Neither should the primary gas stream be cooled to any extent as a result of the injection of an excess of secondary gas.

Since the objectives of this work were to determine whether or not film cooling could be practically applied to plasma torches and whether or not improved energy conversion efficiency would result, no systematic attempt was made to optimize the above parameters. Instead, values were selected that would produce relatively stable torch operation.

Because of its inertness and stability, argon was used in this initial investigation. Other less stable or reactive gases impose undesirable design restrictions for the initial study and their effects would tend to mask salient features of the fundamental processes involved.

## CHAPTER III

### EQUIPMENT AND INSTRUMENTATION

#### Plasma Torch

Plasma torches of many different geometrical configurations and types have been devised and investigated. Usually, however, the designs incorporate rotational symmetry about a central axis and coaxial electrodes separated by an annular gap between which the arc current passes and through which the gas flows.

As illustrated in Figure 1, the torch used in this work is of the gas stabilized constricted arc design. According to John (13) it has been empirically determined that column confinement tends to:

- (1) Increase column voltage gradient, current density, and arc temperature.
- (2) Suppress column motion.
- (3) Heat the gas stream more uniformly.
- (4) Increase the efficiency of the torch.
- (5) Reduce contamination.

In view of the objectives of this project, it is obvious that the inherent characteristics of the confined arc make it the most suitable type.

As shown in Figure 4, the torch constructed for this project consists of the following components: cathode section, gas injection section, constrictor, starting anode section, and terminal anode section.

The cathode section was constructed of red brass with a water cooling chamber provided around the sleeve for the movable cathode. The cathode was made of a  $1/4$ " diameter one per cent thoriated tungsten rod with a 60 degree conical point. The addition of thorium reduces the work function so that a lower cathode tip temperature will maintain the electron flow. Variable arc length was achieved by sliding the cathode in or out to the desired position and tightening the retainer nut.

The gas injection section was constructed so that the gas was introduced tangentially over the cone shaped cathode cooling chamber. By injecting the gas tangentially, a low pressure region developed at the centerline of the constrictor tube, which assisted in aerodynamically maintaining the arc in the center of the constrictor channel and caused the anode attachment point to rotate around the anode surface. The gas injection section was constructed of red brass and had a  $1/8$ " diameter gas injection port.

The constrictor section consisted of a  $3/8$ " inside diameter carbon steel channel surrounded by a brass water cooling jacket. A channel of type L copper was tried because of the greater thermal conductivity of copper, but was replaced by the steel because of the repeated failure of the copper at the silver soldered joint in the brass header. For most effective heat transfer, counterflow was used between the cooling water and the gas flow.

The starting anode section was constructed of an asbestos impregnated insulating material  $3/8$ " thick. A small electrode with a separate electrical connection was provided in this section for starting the arc.

The water cooled terminal anode section consisted of a  $3/8$ " diameter



replaceable copper anode fitted with o-rings and a brass water cooling jacket. All joints were silver soldered.

The film cooled terminal anode section consisted of two concentric shells of carbon steel, an inner shell of type 304 stainless steel, a solid carbon anode insert, a boron nitride nozzle, and a brass, gas cooled current connection. This section was designed so that the secondary gas would reduce side losses by being passed through the current connection and the two outer shells before being injected as a cooling film for the carbon insert. Several materials, including water cooled brass, asbestos impregnated insulation, and fused silica, were found to be unsuitable as nozzle material because of the high heat flux in this region.

The cathode and constrictor sections were separated by a  $1/32$ " thick teflon gasket and the flanges were fastened together with  $1/4$ " diameter nylon bolts. The starting anode, constrictor, and water cooled terminal anode sections were also separated by teflon gaskets and fastened together with nylon bolts. Steel bolts with aluminum oxide insulators and a high temperature adhesive were used to assemble the film cooled terminal anode, starting anode, and constrictor sections. Proper channel alignment was achieved by assembling all sections with a brass drift pin inserted in the channel.

In summary, the mass and current flow in the torches can be described as follows:

- (1) The primary gas is introduced in the gas injection section and swirls around the conical cathode section. The swirling gas then flows around the arc and through the constrictor section into the anode region where the arc attaches.

In the film cooled torch, the secondary gas is circulated through the current connector and the two outer shells of the anode section before being injected tangentially to the anode surface.

(2) The cooling water flowed into the outer shell of each section and swirled around the torch channel. Counterflow between the cooling water and the gas flow was used in the constrictor section.

(3) When the arc is started, an electrically conducting path is established between the anode and the cathode sections. The constrictor section only serves to extend and constrict the arc to enhance gas heating and is electrically insulated from both the cathode and anode. In the water cooled torch, the 3/8" diameter copper channel serves as the anode and the cylindrical carbon insert serves as the anode in the film cooled section. The torch was connected to the generators with insulated copper leads as shown in Figure 5.

#### Calorimeter

In order to determine the energy content of the torch effluent, a water cooled calorimeter of the shell and tube type was constructed. The hot gas stream was pre-cooled in a one inch diameter water cooled copper tube and passed through a water cooled cylindrical coil constructed of 1/2" diameter copper tubing (see Figure 6). In order to reduce the heat transfer between the cooling water jacket and the surrounding atmosphere, insulation was applied to the exterior surfaces.

#### Power Source

The electrical energy was supplied by two Lincoln Arc Welder direct current motor generator welding machines connected in series. Rheostats

were employed to vary the power input to the torch.

#### Cooling Water

City water at pressures of 60 to 80 psig was used in all cooling passages.

#### Gas Supply

Oil free bottled commercial argon was used for all tests.

#### Instrumentation

An Esterline-Angus ac-dc recording utility wattmeter with an accuracy of  $\pm$  two per cent was used to record the power input to the torch. The voltage drop across the arc was measured with a Simpson multipurpose meter and the arc current was measured by passing the current through a calibrated shunt and by recording the voltage drop as indicated by a Leeds and Northrup Model 8686 manually balanced potentiometer.

Voltage ripple and frequency were monitored with a Tektronik Model 555 dual-beam dual-trace oscilloscope.

Temperature determinations at the various locations in the water and gas circuits were made with 26 gauge copper-constantan thermocouples. A 24 gauge iron-constantan thermocouple was used to determine the temperature of the exterior surface of the film cooled terminal anode section. A Leeds and Northrup potentiometer described above was used to record the thermocouple outputs.

The rate of flow of the cooling water to the various sections of the torch and calorimeter was determined through the use of orifices and U-tube mercury manometers. The orifices were shop fabricated and

calibrated after installation. Each orifice was calibrated by weighing the flow during a given time interval for a series of pressure drops.

The total flow of argon was measured by passing the effluent from the calorimeter into an American Model 425 gas meter calibrated in the local utility company's lab to  $\pm$  two per cent.

The secondary gas flow was monitored by a variable area type meter at the regulator with an accuracy of only  $\pm$  ten per cent. The secondary flow rates recorded were obtained by ascertaining the primary flow rate and subtracting this value from the total flow rate.

## CHAPTER IV

### TESTING PROCEDURE AND RESULTS

During design and construction of the torch, emphasis was placed on geometrical similarity between the water cooled and film cooled torches. In fact, only the terminal anode sections were changed during the test runs. Consequently, during the tests, care was taken to evaluate both the water cooled and the film cooled anode under the same operating conditions.

Before starting the arc, it was first necessary to ascertain that the proper quantity of water was supplied to the various cooling passages and that the required gas flow rate had been established. Then, the power supplies were started. Starting the arc can be accomplished either by imposing a high voltage across the electrodes and using a high frequency arc to achieve ignition or by establishing contact between the two electrodes. In the absence of any high frequency starting equipment, ignition for the tests was achieved by establishing contact between the two electrodes. The starting anode section was equipped with a separate power connection consisting of a 1/8" diameter steel screw and a 1/16" diameter tungsten rod as shown in Figures 4b and 5. A small quantity of steel wool was injected into the channel through the screw hole in the starting anode and the 1/16" diameter tungsten rod was placed in contact with the steel wool. As a result, the steel wool was at the same potential as the terminal anode when the switch was closed. Then, by sliding the 1/4" diameter cathode down the channel until contact was made with the steel wool, the arc was started.

The starting anode switch was then opened and the cathode was withdrawn until the desired arc length was established.

An effort was made to achieve a steady state operating condition before any data were recorded. The approach to steady state was determined by closely observing the thermal measurements. In the tests made using the water cooled anode, the torch and calorimeter cooling water exit temperatures were used as indicators. Most test runs required 10 to 15 minutes to reach an approximate steady state condition. In the film cooled anode tests, the temperature of the exterior surface of the anode and the calorimeter exit water temperature were used as the determining factors. Due to the mass of the film cooled anode section, transient conditions were usually observed for 15 to 20 minutes. After steady state had been achieved, the thermal and electrical readings were recorded at five minute intervals for 10 to 20 minutes. During the test runs, the generator rheostats were adjusted in an attempt to maintain constant energy input.

The two independent parameters used as operating variables were total gas flow and power input. A series of tests was made during which the gas flow remained constant while the power input was varied incrementally. Five different power input values were selected with the lowest value chosen as the point at which a further reduction in power resulted in interruption of the arc. The upper bound of the power input was determined by the water cooling system. Higher values could possibly be used with the same torch provided that a high pressure pumping system was employed. The upper bound of the film cooled anode tests was selected to match the limits of the water cooled tests. The power input range was

divided into four approximately equal increments.

Six such series of tests were conducted for the water cooled torch and four series for the film cooled torch - each at a different value of gas flow rate. During the film cooled tests, the total gas flow values - sum of the primary and secondary flow - were selected to match the flow rates used in the water cooled tests.

As noted in Chapter II, no systematic attempt was made to optimize operating variables; however, two series of tests were conducted utilizing the film cooled anode, in which the values of secondary and primary gas flow rates were each varied while the power input remained constant, in an effort to determine whether variations in either flow rate exhibited significant influence on the torch operation.

The results of the test runs discussed above are tabulated in Tables 1 and 2. Note that during the tests with the water cooled torch, the maximum arc current is approximately 120 amps for the two lowest values of gas flow rate. Efficiency for the water cooled torch varies from 57 to 79 per cent.

During the tests with the film cooled torch, the minimum arc current was approximately 58 amps and the maximum current for the low gas flow rates was approximately 120 amps. Efficiency for the film cooled torch varies from 78.5 to 93 per cent.

Figure 8 is a plot of torch efficiency versus arc current for both the water cooled and the film cooled torches. Figure 9 is a plot of efficiency for the film cooled torch versus secondary (coolant) gas flow with constant primary gas flow and arc current.

## CHAPTER V

### DISCUSSION OF RESULTS

Torch efficiency has been defined earlier as the ratio of the thermal energy output to the electrical energy input or:

$$E = \frac{Q(\text{gas})}{P_{\text{in}}} = \frac{Q_{\text{cal}} - Q_{\text{arc rad}}}{P_{\text{in}}}$$

The term  $Q_{\text{cal}}$  is the energy content of the calorimetrically measured torch effluent,  $Q_{\text{arc rad}}$  is the thermal radiation from the arc and the torch channel to the calorimeter, and  $P_{\text{in}}$  is the electrical energy input. During this investigation, however, the term  $Q_{\text{arc rad}}$  has been omitted since Kinney, et al. (7) found in a similar investigation with a transpiration cooled anode that the magnitude of this term was generally less than the uncertainty of the calorimeter measurements.

The efficiency of both torches decreased with increasing energy input and results primarily from the increasing radiation losses as the arc column temperature increases with higher arc current. Also, since the arc diameter is inversely proportional to the thermal conductivity of the plasma (5) which increases with temperature and arc current (13), the inner flow region (see Figure 1) becomes fully developed in a shorter length as arc current increases. As a result, the convective losses in the constrictor section increase. The energy input to the anode increases with increasing current because of the greater number of electrons releasing energy proportional to



the surface work function energy. These observations may be verified by noting that the constrictor heat load  $Q_{con}$ , and the anode head gain  $Q_{an}$ , increase with arc current.

The efficiency of both torches appears to be essentially independent of gas flow rate for the range tested. Some variation is noted; however, no definite trends are evident. It appears that the flow rate intervals were too small to cause a noticeable change in the efficiency. Note also that in Figure 8, the film cooled torch efficiency was found to be independent of the secondary gas flow rate. Although the two test runs in which the secondary gas flow was varied are certainly not conclusive, they do give an indication that for a secondary flow rate above a certain minimum value, the efficiency is essentially invariant with respect to the coolant flow. During operation with a coolant flow above the minimum value, the outer flow region or protective film is extended the length of the anode section. During operation with a coolant flow below this value, however, the entire length of the anode would not be protected and, as a result, the torch efficiency would be reduced because of the increased convection, conduction and radiation losses. Experimental work (11) using air at low temperatures and low velocities helps substantiate these conclusions.

Figure 9 provides a graphic illustration of the energy flow for the film cooled torch. The terms  $Q_{rad}$  and  $Q_{conv}$  refer to the radiation and convection losses respectively from the outer shell of the anode section.  $Q_g$  is the enthalpy of the effluent due to the film coolant flow. For the water cooled anode, the flow direction of  $Q_g$  is reversed, since this quantity of energy is removed by the cooling water. The term,  $Q_e$ , which is the

energy transferred from the arc to the gas, is approximated by using the energy content of the water cooled torch effluent when operating at the same power level, gas flow, etc. The terms,  $Q_{\text{cath}}$  and  $Q_{\text{con}}$ , represent the losses in the cathode and constrictor sections.  $Q_{\text{cal}}$  is the energy content of the torch effluent as measured by the calorimeter.

$Q_{\text{cath}}$  was less than 2.5 per cent and  $Q_{\text{rad}}$  and  $Q_{\text{conv}}$  were each less than 1.0 per cent of the power input.  $Q_{\text{con}}$  varied from 5.0 to 17.0 per cent,  $Q_e$  varied from 57 to 65 per cent, and  $Q_g$  varied from 20 to 25 per cent. It may be concluded from this analysis and the efficiency comparison shown in Figure 7 that the torch with the film cooled anode is approximately 20 per cent more efficient than the fully water cooled torch over the operating range tested. The film cooled torch is more efficient because of the difference in energy losses in the anode section as approximated by the term,  $Q_g$ , in Figure 9.

Although other film cooled torch results are not available for comparison, results from a similar investigation (7) of a transpiration cooled anode indicate that both regenerative cooling methods produce efficiencies approximately 20 per cent higher than a water cooled torch. The transpiration cooled torch operated at between 80 and 90 per cent efficiency for gas flow between 0.25 and 0.50 lbs/min.

The film cooled torch arc current and gas flow rate values were selected to match the values used in the water cooled test as explained in Chapter IV. The arc current can be increased provided that the coolant gas flow is increased sufficiently to protect the anode surface. At higher values of arc current, it would be desirable to use a segmented anode designed so that the coolant could be injected at more than one location

along the anode surface. The arc current is limited by the effectiveness of a coolant gas film. Above a certain value of arc current, the film will not protect the anode surface. Consequently, for operation at higher values of arc current, the anode should be constructed of a metalized or carbonized ceramic material. Tungsten, although it has a slightly lower melting temperature than carbon, has higher thermal and electrical conductivity, which helps to maintain a cooler surface at higher currents.

An analysis of the accumulated errors in the energy calculations indicates that the torch efficiencies shown in Tables 1 and 2 are accurate in the extreme case to  $\pm$  seven per cent. The accumulated errors occur in the power input and calorimeter energy measurements.

## CHAPTER VI

### CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the investigation of a plasma torch equipped with a film cooled anode:

(1) The film cooled torch is a promising tool for efficient plasma generation.

(2) For the range of variables studied, the film cooled torch is approximately 20 per cent more efficient than a comparable water cooled torch.

(3) The film cooled torch is capable of stable operation for extended time intervals if operated within certain limits of mass flow and current.

For further study, the following recommendations are offered:

(1) Optimize such operating variables as arc current and secondary gas flow rate and enthalpy.

(2) Investigate stage film cooling, using a torch equipped with a segmented anode for higher arc current capability.

(3) Investigate a film cooled torch with an anode constructed of carbonized ceramics or tungsten to determine endurance.

Table 1. Water Cooled Torch Test Results

Gas Flow Lbs/ Min	Arc Current Amps	Voltage	Power Input KW	Q <sub>cal</sub> B/Min	Q <sub>cath</sub> B/Min	Q <sub>con</sub> B/Min	Q <sub>an</sub> B/Min	Efficiency
.20	34.5	70.0	2.4	105.0	8.6	6.4	28.4	79.0
	60.0	70.0	4.2	169.6	12.9	21.8	47.2	71.0
	90.5	74.0	6.7	242.2	16.2	55.0	76.9	63.6
	123.0	75.0	9.2	319.0	20.5	95.9	107.9	60.6
.25	37.5	70.0	2.6	117.0	9.8	11.5	33.8	78.4
	60.2	72.5	4.4	183.5	13.0	23.0	50.0	74.0
	90.3	77.0	7.0	273.0	19.5	58.8	77.0	69.2
	121.8	77.0	9.4	320.0	15.1	99.8	105.3	60.2
.31	37.5	73.0	2.7	115.0	11.9	14.1	26.2	74.0
	60.6	73.0	4.4	170.5	15.1	29.4	44.2	68.3
	90.8	76.0	6.9	255.0	16.2	74.2	73.0	65.0
	120.2	82.0	9.9	341.0	16.2	101.1	98.0	60.9
	152.6	79.0	12.1	370.0	12.7	151.1	108.0	54.0
.39	36.8	71.0	2.7	115.0	7.5	5.1	29.0	76.5
	62.4	72.0	4.5	170.5	9.7	25.6	49.7	66.9
	92.3	77.0	7.1	258.0	11.9	60.2	77.2	63.4
	121.4	81.0	9.8	345.0	14.0	98.6	103.5	61.9
	153.9	84.0	13.0	424.0	15.1	145.9	132.5	57.6
.45	39.9	72.5	2.9	123.1	4.6	9.0	32.6	75.0
	60.3	75.0	4.5	190.5	6.4	24.3	54.4	74.0
	95.3	80.0	7.6	302.0	8.2	62.6	88.4	69.6
	120.2	75.5	9.1	337.5	9.1	94.6	103.2	65.4
	150.0	79.0	11.9	402.0	11.8	144.8	127.9	59.8
.50	36.2	74.0	2.7	107.1	6.4	11.7	22.2	70.5
	60.6	72.5	4.3	166.8	7.3	28.6	41.8	66.9
	92.9	74.0	6.9	246.1	8.2	61.1	69.2	63.1
	122.6	77.0	9.4	323.0	10.0	102.5	98.0	60.2
	151.5	81.0	12.3	398.0	10.0	156.0	127.9	57.2

Table 2. Film Cooled Torch Test Results

Gas Flow Lbs/Min	Arc Current Amps	Voltage	Power Input KW	Q <sub>cal</sub> B/Min	Q <sub>cath</sub> B/Min	Q <sub>con</sub> B/Min	Efficiency
.35	57.9	67.5	3.9	187.2	4.9	16.0	84.5
	96.9	74.0	6.7	335.0	4.9	42.6	87.5
	123.3	74.0	8.5	402.0	6.9	66.5	82.5
.44	59.7	71.0	4.1	211.0	5.9	20.0	89.0
	92.7	74.0	6.8	324.0	6.9	42.6	84.0
	119.1	76.0	8.8	414.0	6.9	69.1	83.0
.50	59.3	75.0	4.4	234.0	5.9	13.3	93.0
	90.0	79.0	7.0	362.0	7.8	45.2	87.5
	123.9	82.0	9.9	484.0	8.8	82.4	85.5
	151.8	85.0	12.5	584.0	10.8	123.5	82.5
.57	58.7	75.0	4.3	210.5	6.8	19.9	85.5
	93.6	79.0	7.2	350.5	6.8	45.2	85.5
	122.4	82.0	9.6	456.0	6.8	75.7	83.4
	151.7	84.5	12.3	546.0	7.8	111.6	78.5
.33	60.0	75.0	4.4	202.5	8.8	26.6	80.6
.39	60.0	75.0	4.4	198.5	7.9	25.3	79.0
.47	60.7	76.0	4.5	206.5	8.8	27.9	81.0
.58	60.5	76.0	4.5	206.5	9.8	30.6	81.0
.33	120.9	80.0	9.6	434.0	10.8	95.7	79.5
.40	122.1	80.0	9.6	434.0	10.8	94.4	79.5
.48	120.0	80.0	9.4	418.0	11.8	93.1	78.5
.56	120.5	80.5	9.5	425.0	11.8	98.4	78.5

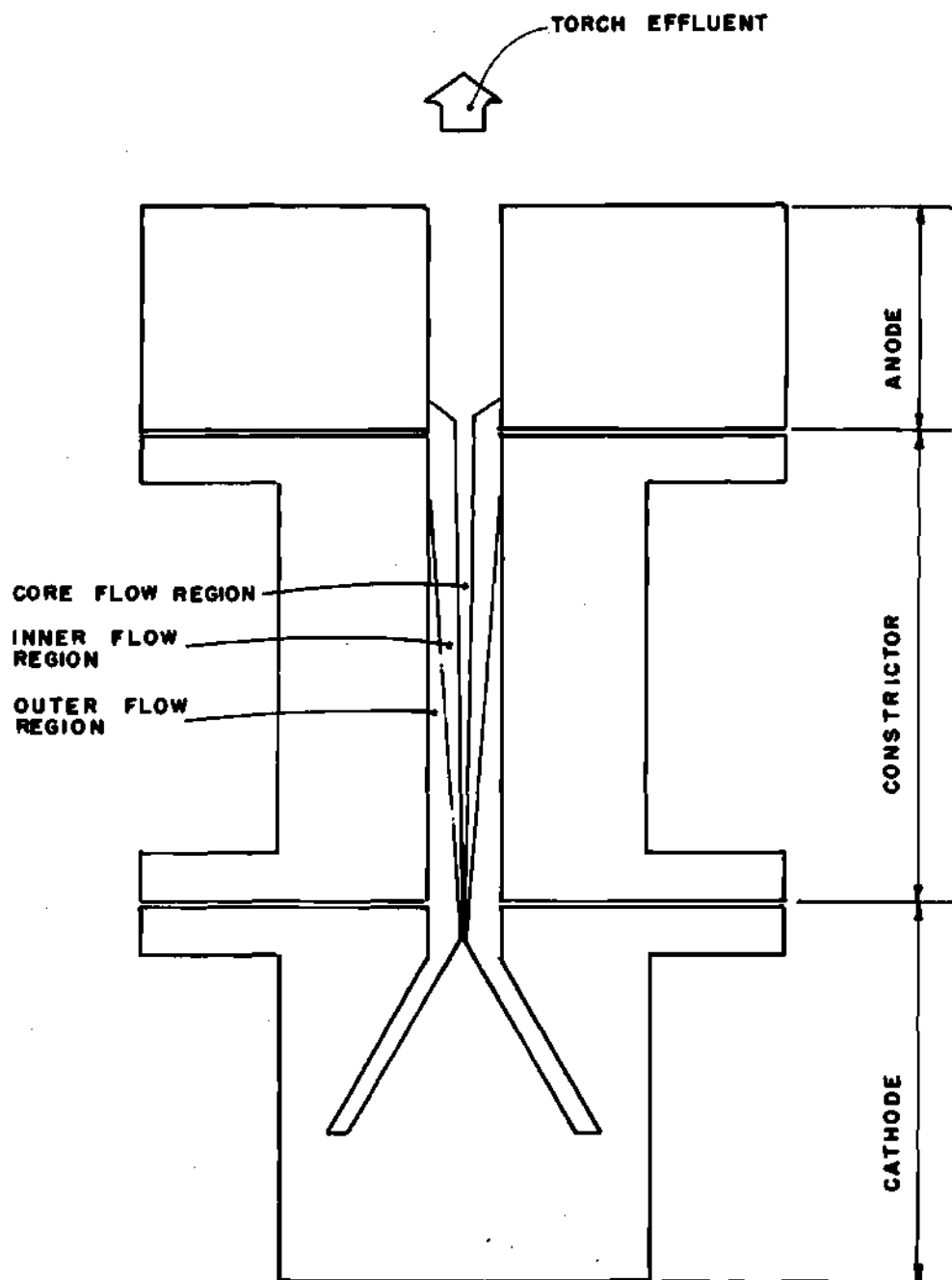
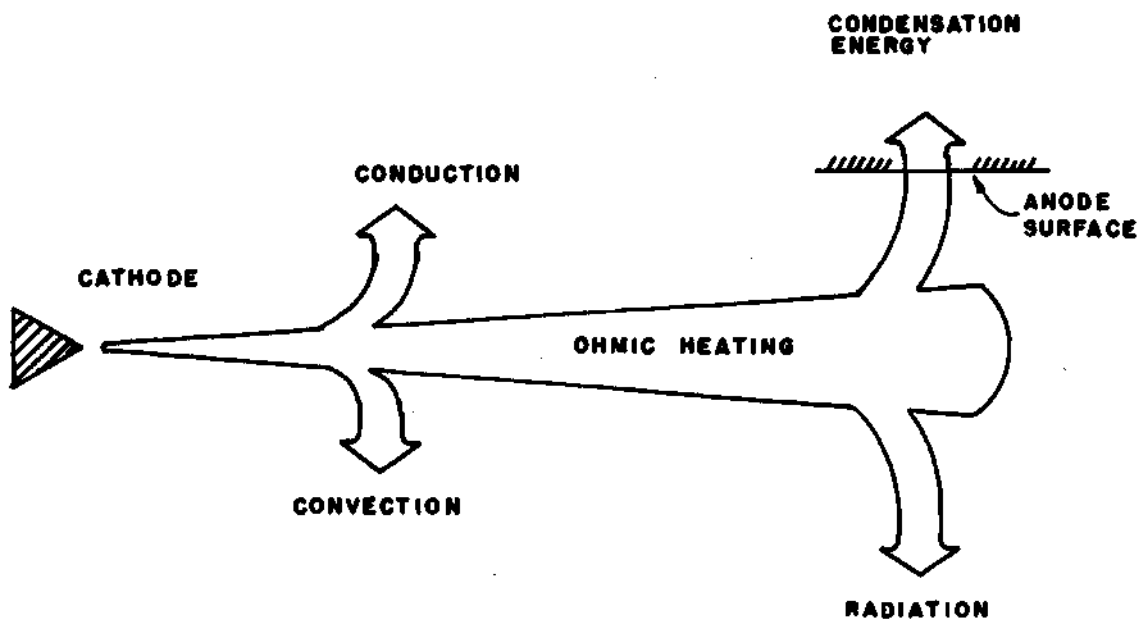


FIGURE 1  
PLASMA TORCH SCHEMATIC



**FIGURE 2**  
**ARC ENERGY TRANSFER PROCESSES**



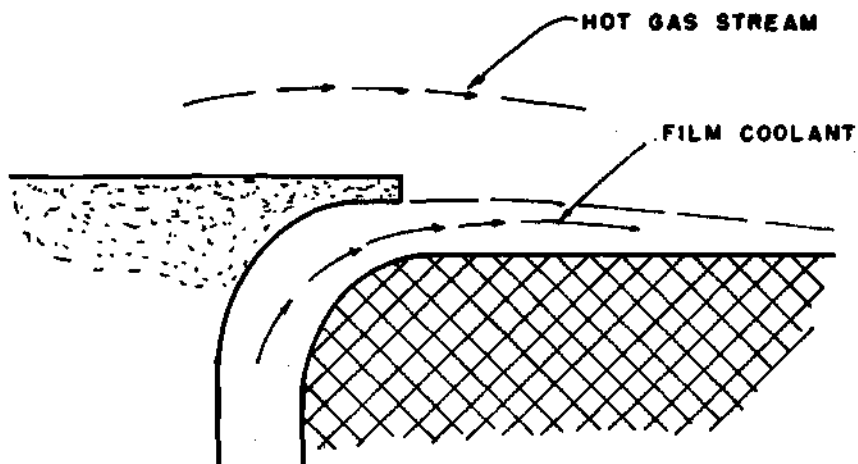


FIGURE 3  
FILM COOLING

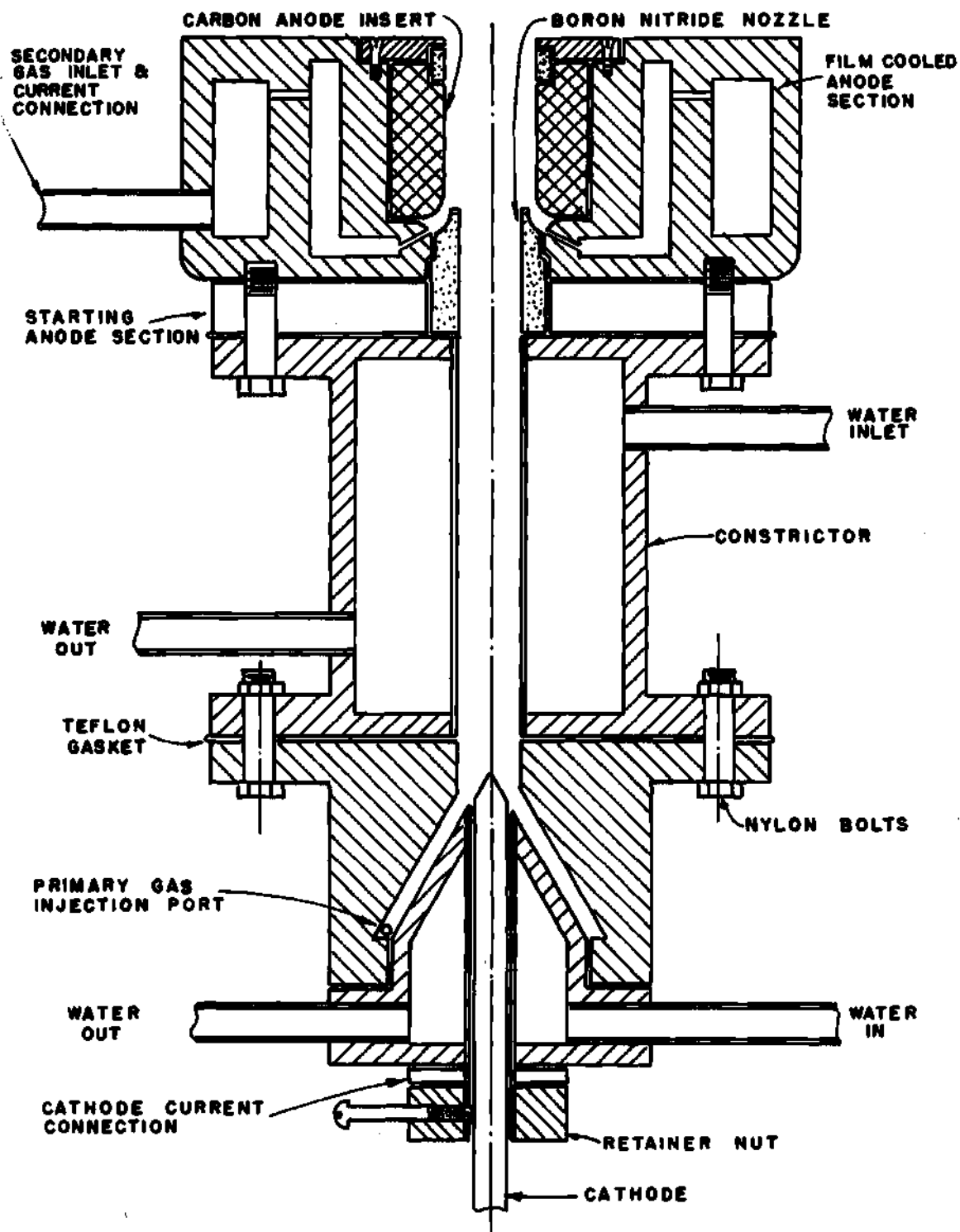


FIGURE 4A  
PLASMA TORCH WITH FILM COOLED ANODE  
FULL SIZE

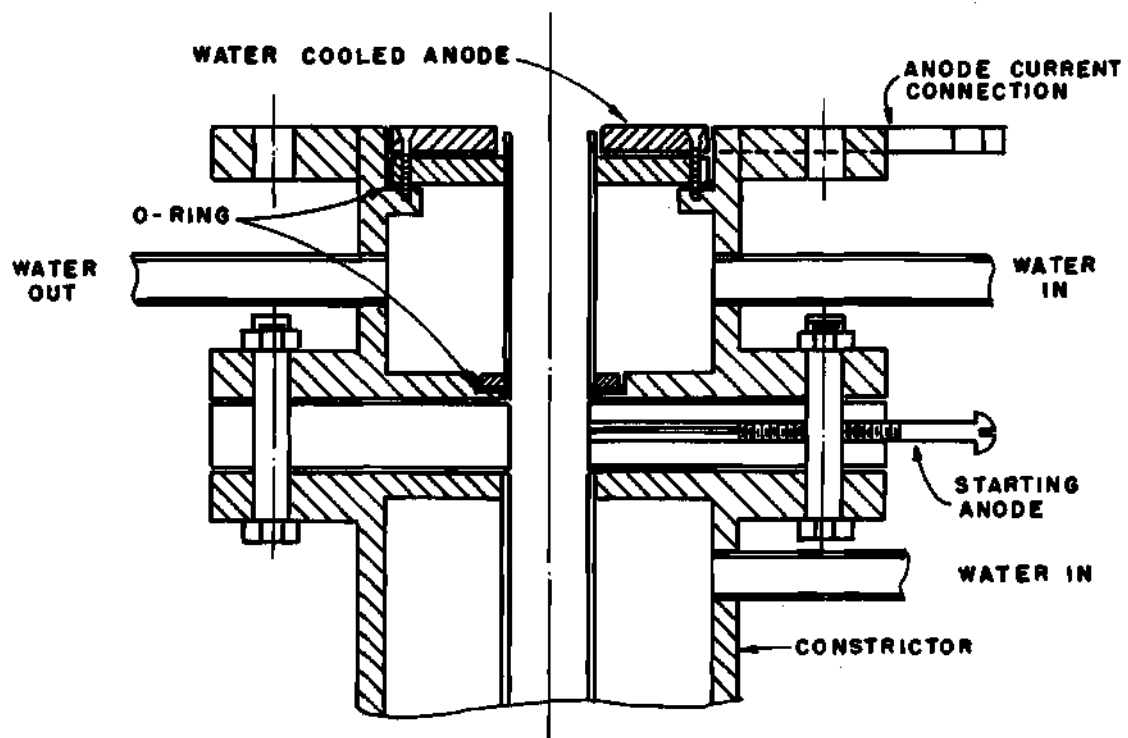


FIGURE 4B  
WATER COOLED ANODE  
FULL SIZE

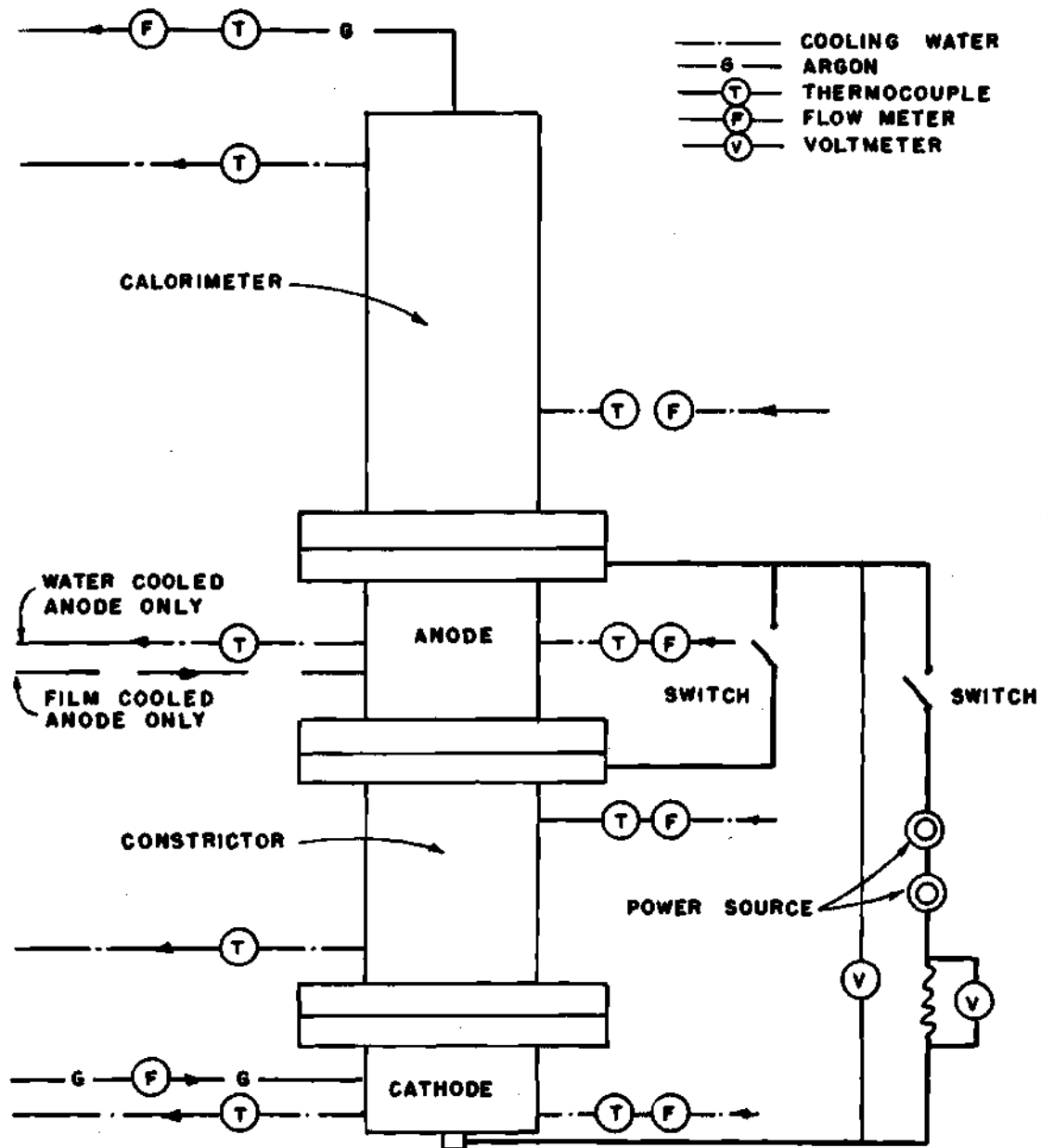


FIGURE 5  
EXPERIMENTAL APPARATUS SCHEMATIC

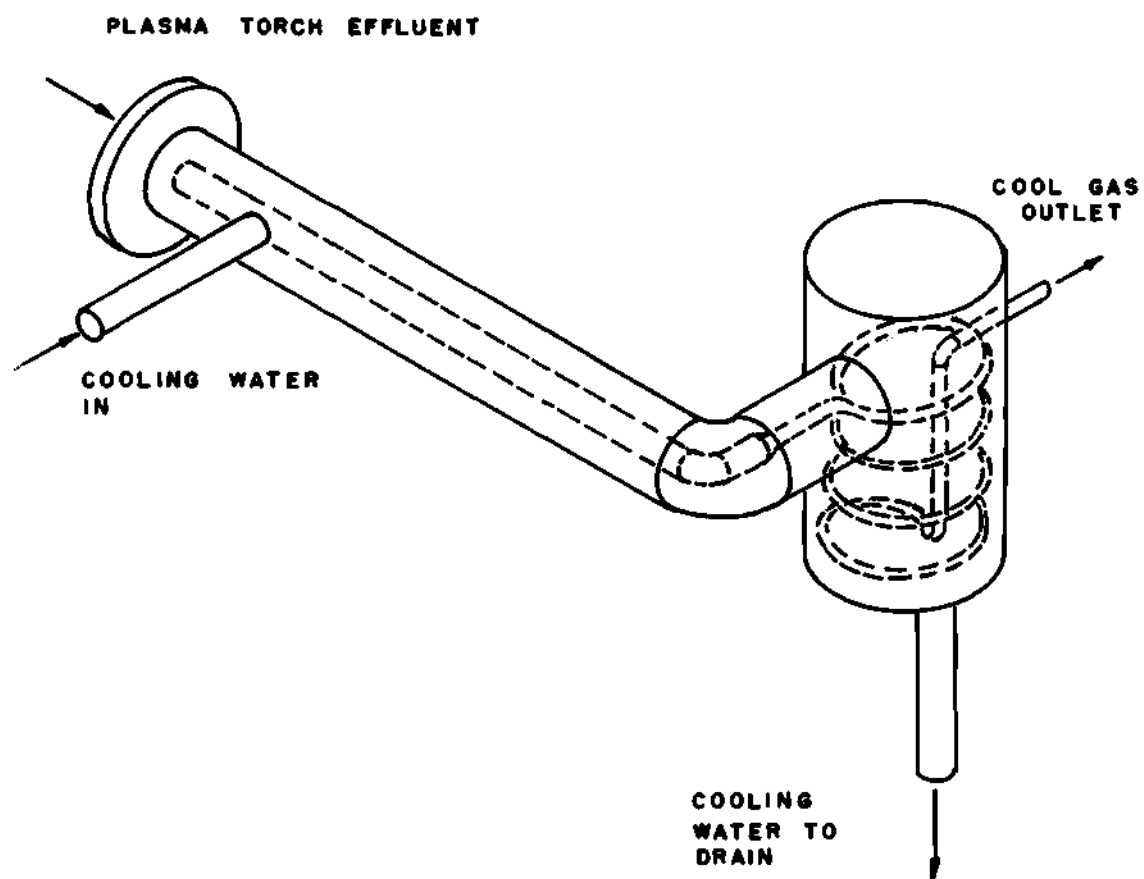


FIGURE 6  
CALORIMETER

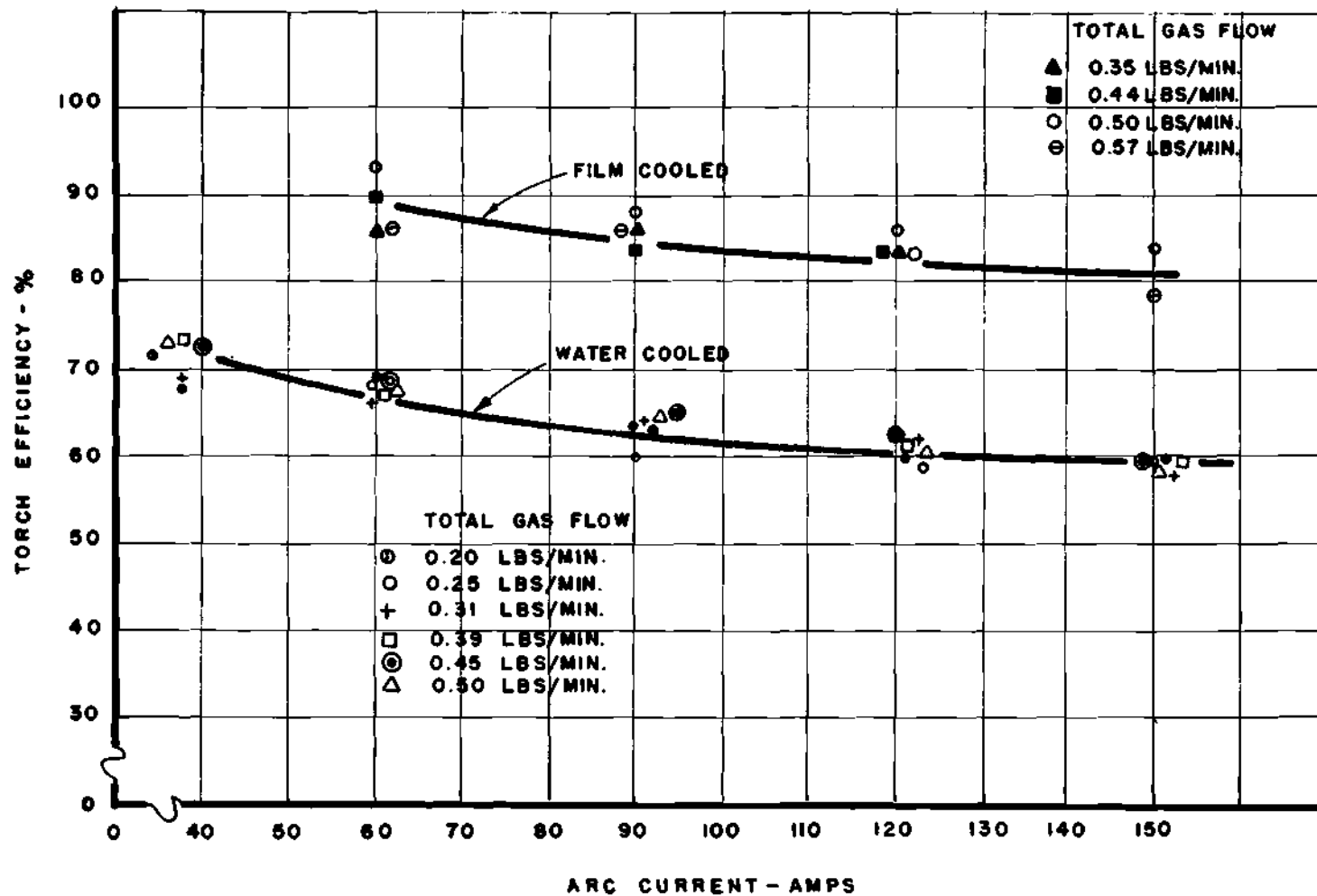


FIGURE 7  
TORCH EFFICIENCY VERSUS ARC CURRENT

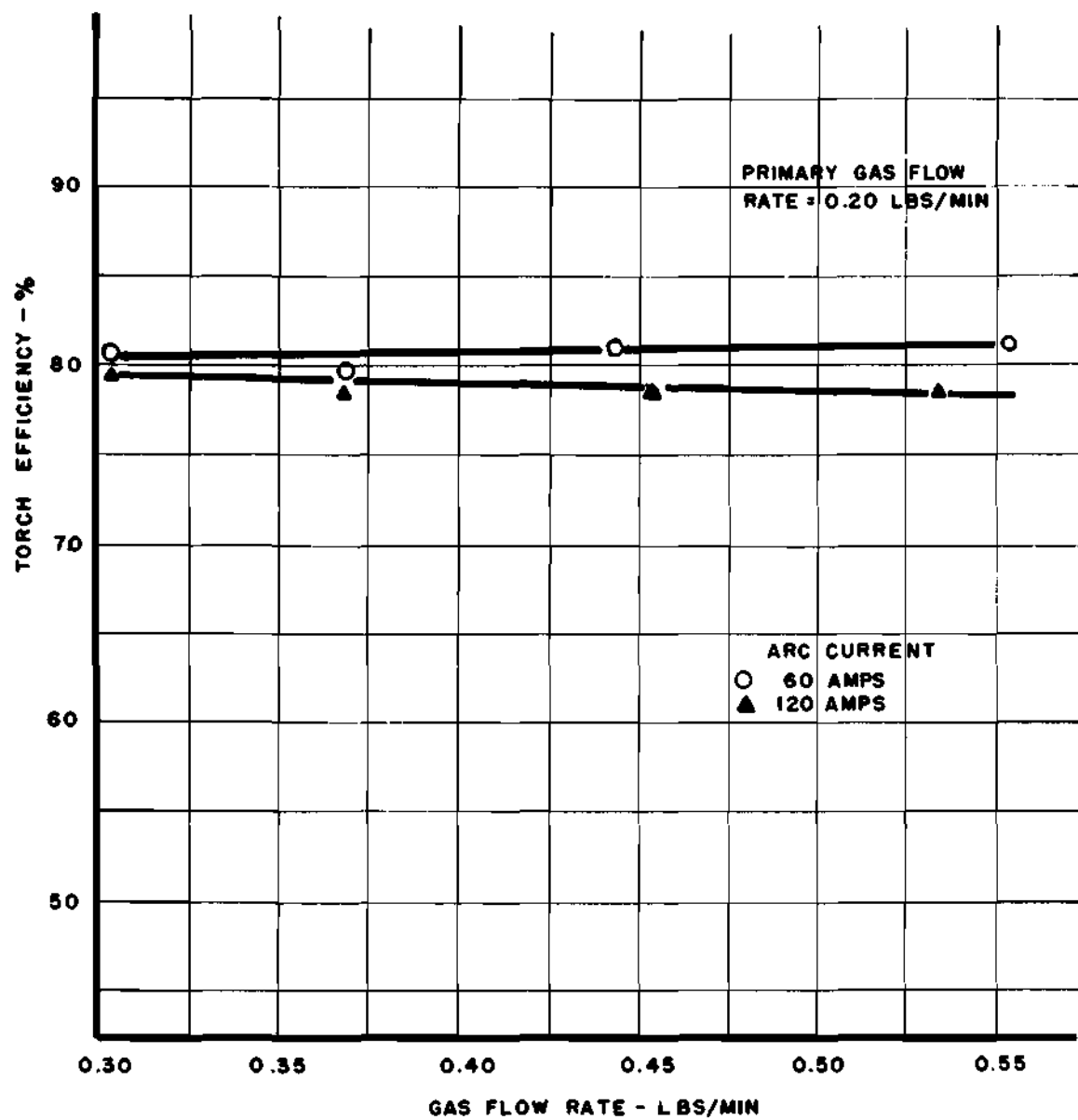


FIGURE 8  
TORCH EFFICIENCY VERSUS GAS FLOW RATE

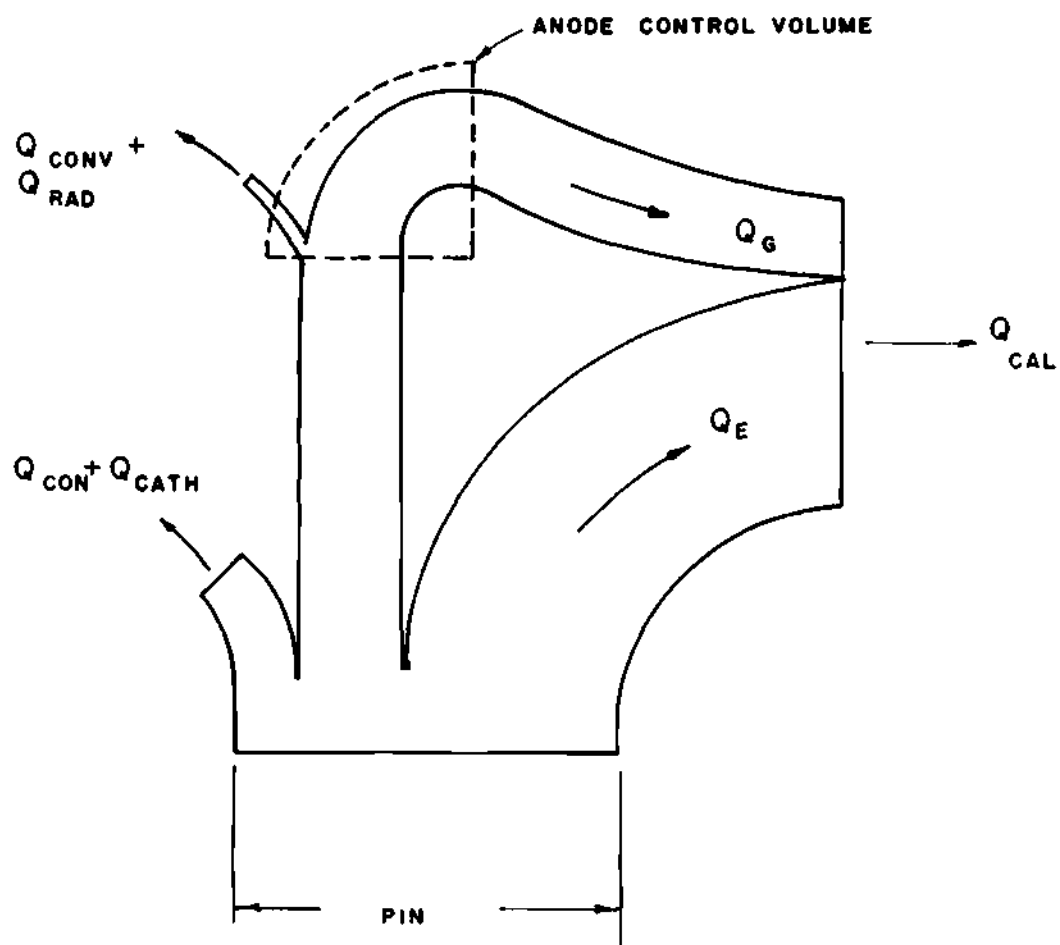


FIGURE 9  
ENERGY FLOW DIAGRAM



## SAMPLE CALCULATIONS

The energy balance and efficiency calculations for the typical operating condition listed below were made in the following manner:

Anode material:	Copper
Gas flow rate:	0.39 lbs/min.
Voltage:	72.0 volts
Arc current:	62.4 amps
Water inlet temp.:	51.9° F
Water outlet temp. - Cathode:	52.8° F
Water outlet temp. - Constrictor:	53.9° F
Water outlet temp. - Anode:	55.5° F
Water outlet temp. - Calorimeter:	56.2° F
Water flow rate - Cathode:	10.8 lbs/min.
Water flow rate - Constrictor:	12.8 lbs/min.
Water flow rate - Anode:	13.8 lbs/min.
Water flow rate - Calorimeter:	39.7 lbs/min.

Cathode losses = (water flow rate) (spec. heat) (water temp. diff.)

$$\begin{aligned}
 Q_{\text{cath}} &= m c \Delta T \\
 &= (10.8 \text{ lbs/min}) (1.0 \text{ B/lb-}^{\circ}\text{F}) (52.8-51.9)^{\circ}\text{F} \\
 &= 9.7 \text{ B/min.}
 \end{aligned}$$

Constrictor losses = (water flow rate) (spec. heat) (water temp. diff.)

$$\begin{aligned}
 Q_{\text{con}} &= m c \Delta T \\
 &= (12.8 \text{ lbs/min}) (1.0 \text{ B/lb-}^{\circ}\text{F}) (53.9-51.9)^{\circ}\text{F} \\
 &= 25.6 \text{ B/min.}
 \end{aligned}$$

Anode losses = (water flow rate) (spec. heat) (water temp. diff.)

$$\begin{aligned}
 Q_{\text{an}} &= m c \Delta T \\
 &= (13.8 \text{ lbs/min}) (1.0 \text{ B/lb-}^{\circ}\text{F}) (55.5-51.9)^{\circ}\text{F} \\
 &= 49.7 \text{ B/min.}
 \end{aligned}$$

Calorimeter gain = (water flow rate) (spec. heat) (water temp. diff.)

$$\begin{aligned} Q_{\text{cal}} &= m c \Delta T \\ &= (39.7 \text{ lbs/min}) (1.0 \text{ B/lb-}^{\circ}\text{F}) (56.2-51.9)^{\circ} \text{ F} \\ &= 170.5 \text{ B/min.} \end{aligned}$$

Energy input = (volts) (amps)

$$\begin{aligned} P_{\text{in}} &= (72.0 \text{ volts}) (62.4 \text{ amps}) (3.41 \text{ B/volt-amp}) / 60 \frac{\text{min.}}{\text{hr.}} \\ &= 255.0 \text{ B/min.} \end{aligned}$$

Efficiency =  $\frac{\text{Calorimeter gain}}{\text{Energy input}}$

$$\begin{aligned} &= \frac{Q_{\text{cal}}}{P_{\text{in}}} \\ &= \frac{170.5 \text{ B/min.}}{255.0 \text{ B/min.}} \times 100 = 66.9 \text{ per cent} \end{aligned}$$

Calculations for the test utilizing the film cooled carbon anode were made in a similar manner, except for the anode losses, which were calculated as follows:

Anode exterior surface temperature:  $456^{\circ} \text{ F}$

Room temperature:  $70^{\circ} \text{ F}$

Free convection losses = (heat transfer coefficient) (area) (temp. diff.)

$$\begin{aligned} Q_{\text{conv}} &= h A \Delta T \\ h &= 0.25 \left( \frac{\Delta T}{D} \right)^{1/4} (15) \\ Q_{\text{conv}} &= (0.25) (\pi) (D) (L) \left( \frac{\Delta T}{D} \right)^{1/4} \Delta T \\ &= (0.25) (\pi) (0.125) (0.333)^{3/4} (386)^{5/4} \\ Q_{\text{conv}} &= 1.15 \text{ B/min.} \end{aligned}$$

$$\text{Radiation losses} = \epsilon \sigma (T_1^4 - T_2^4) (A)$$

$T_1$  = Exterior surface temperature

$T_2$  = Room temperature

For steel:  $\epsilon \cong 0.79$  (15)

$$Q_{\text{rad}} = (0.79) (.1713 \times 10^{-8}) (\pi \text{ DL}) (916^4 - 530^4)^\circ \text{ R}$$

$$Q_{\text{rad}} = (0.79) (.1713 \times 10^{-8}) (\pi) (0.333) (0.125) (916^4 - 530^4)^\circ \text{ R}$$

$$= 1.87 \text{ B/min}$$

$$Q_{\text{an}} = 1.15 + 1.87 = 3.02 \text{ B/min.}$$

# ERROR ANALYSIS

The calculated efficiencies shown in Tables 1 and 2 are only accurate to a certain degree because of the listed inaccuracies of the instrumentation and the errors which occur in recording the data. As stated in Chapter II, the inaccuracy of the wattmeter used to measure energy input,  $P_{in}$ , is  $\pm$  two per cent of the full scale reading. The accuracy of the potentiometer used to measure thermocouple output was  $\pm$  0.05 per cent of the reading plus three mv and the accuracy of the thermocouples was  $\pm$  0.1° F. It is estimated that the mercury manometer used to measure the cooling water flow rate could be read to within  $\pm$  0.1 inches Hg.

For the test using the film cooled anode operating at a gas flow rate of 0.44 lbs/min and energy input of 8.8 kw, the possible error in efficiency is:

$$P_{in} = 8.8 \text{ kw} \pm (.02) (10 \text{ kw})$$

$$= 8.8 \text{ kw} \pm 0.2 \text{ kw}$$

$$= 500.0 \text{ B/min.} \pm 10.9 \text{ B/min.}$$

$$Q_{cal} = m c \Delta T$$

$$= (39.0 \pm 0.75) \text{ lbs/min.} (1.0 \text{ B/lb-}^{\circ}\text{F}) [(62.9 \pm 0.1) - (52.3 \pm 0.1)]$$

$$= 414.0 \text{ B/min} \pm 22.0 \text{ B/min.}$$

$$\text{Efficiency} = \frac{414.0 \pm 22.0}{500.0 \pm 10.9} \times 100 = 83.0 \pm 6.2 \text{ per cent.}$$

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